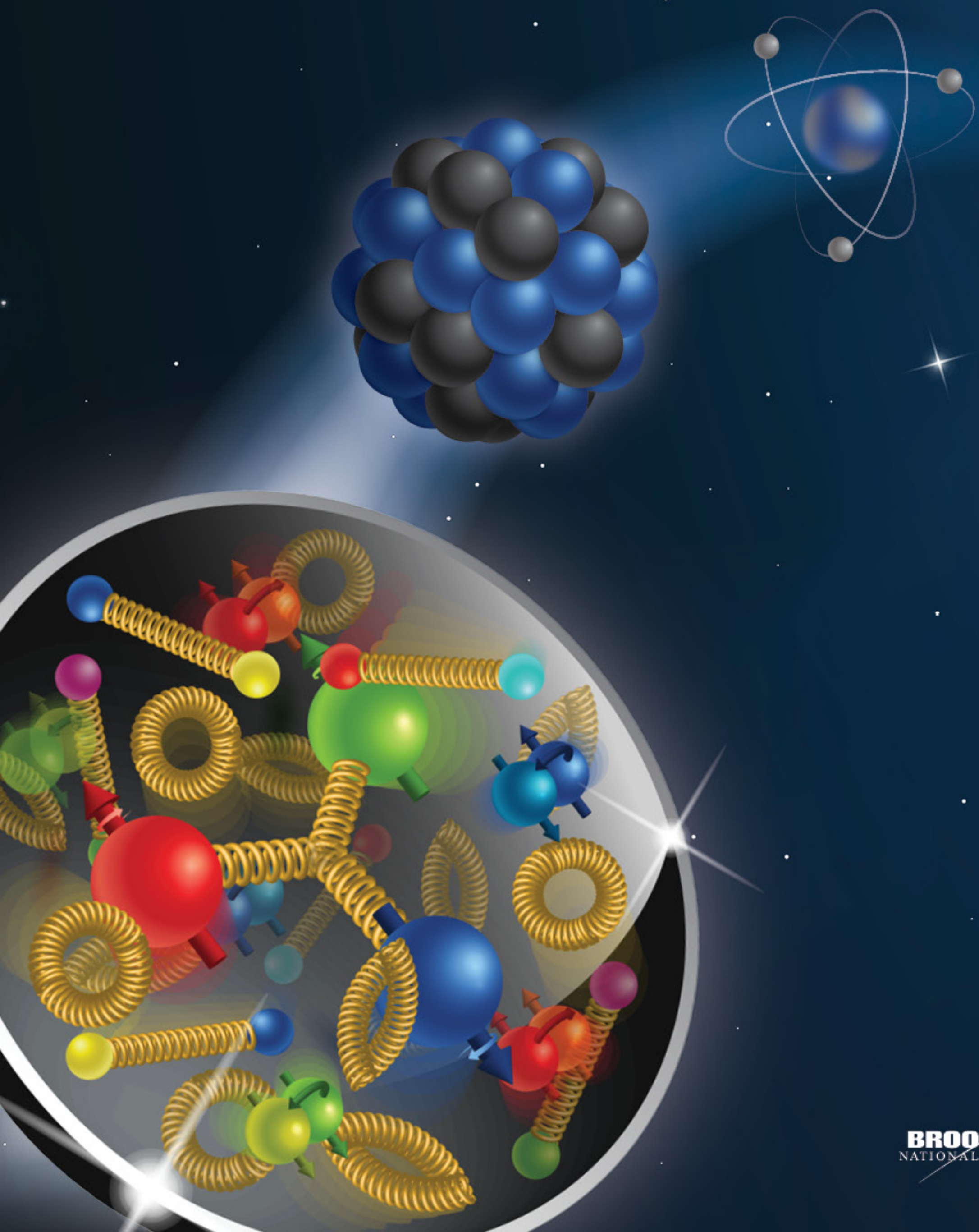


EIC Accelerator Overview

Christoph Montag, BNL

RHIC/AGS Users Meeting

June 9-11, 2021

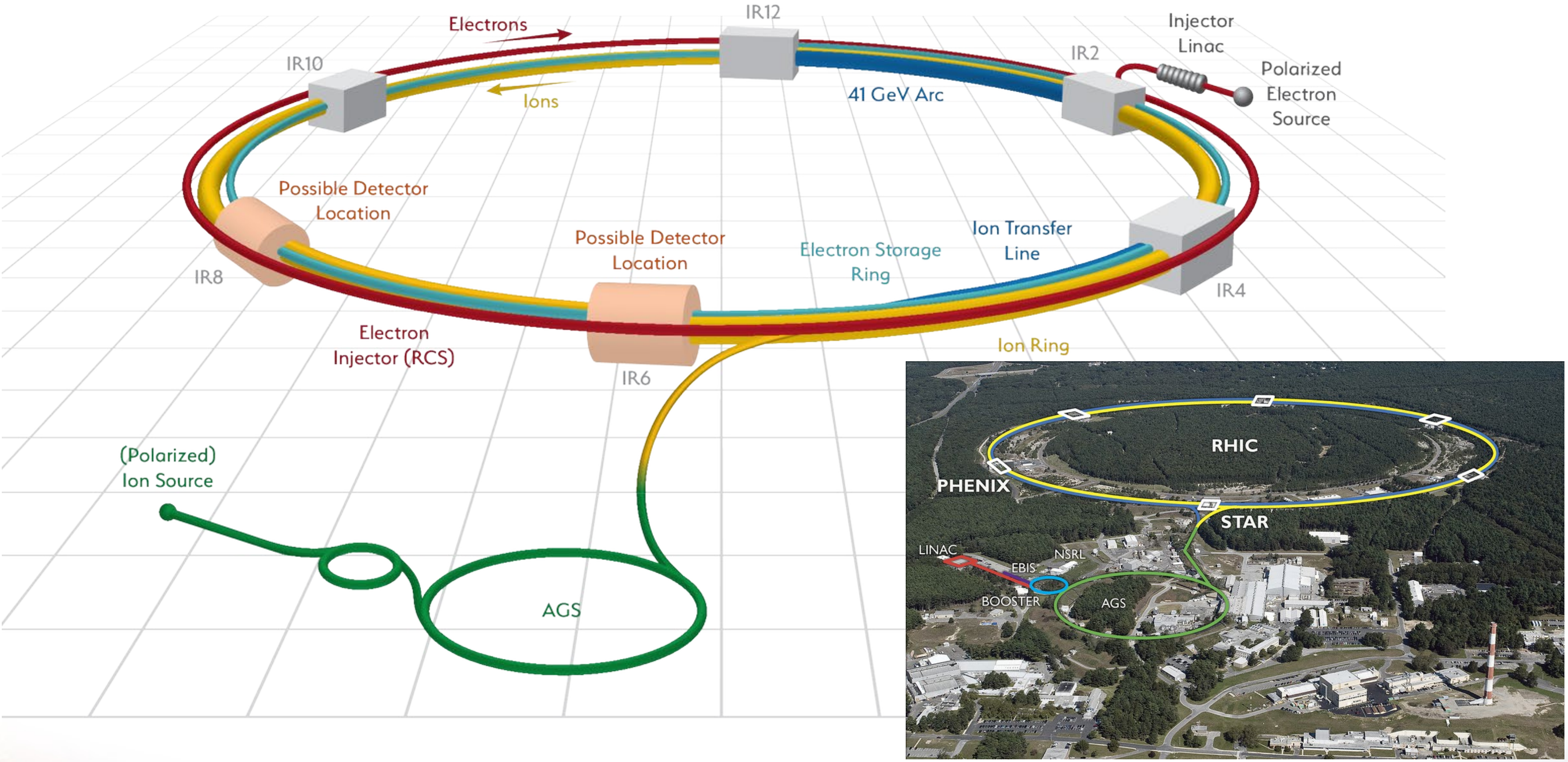
Electron-Ion Collider

BROOKHAVEN NATIONAL LABORATORY Jefferson Lab U.S. DEPARTMENT OF ENERGY Office of Science

EIC Design Concept (in a nutshell)

- Take one RHIC ring with its entire injector complex as the EIC hadron ring
- Add electron cooling to lower emittance and counteract IBS
- Modify the hadron ring to be suitable for EIC beam parameters
- Install an electron storage ring in the existing tunnel
- Use a spin-transparent rapid-cycling synchrotron as full-energy polarized electron injector for rapid bunch replacement to counteract depolarization
- Build a high luminosity interaction region that fulfills acceptance requirements

Facility layout



Electron complex to be installed in existing RHIC tunnel – cost effective

Parameters for Highest Luminosity

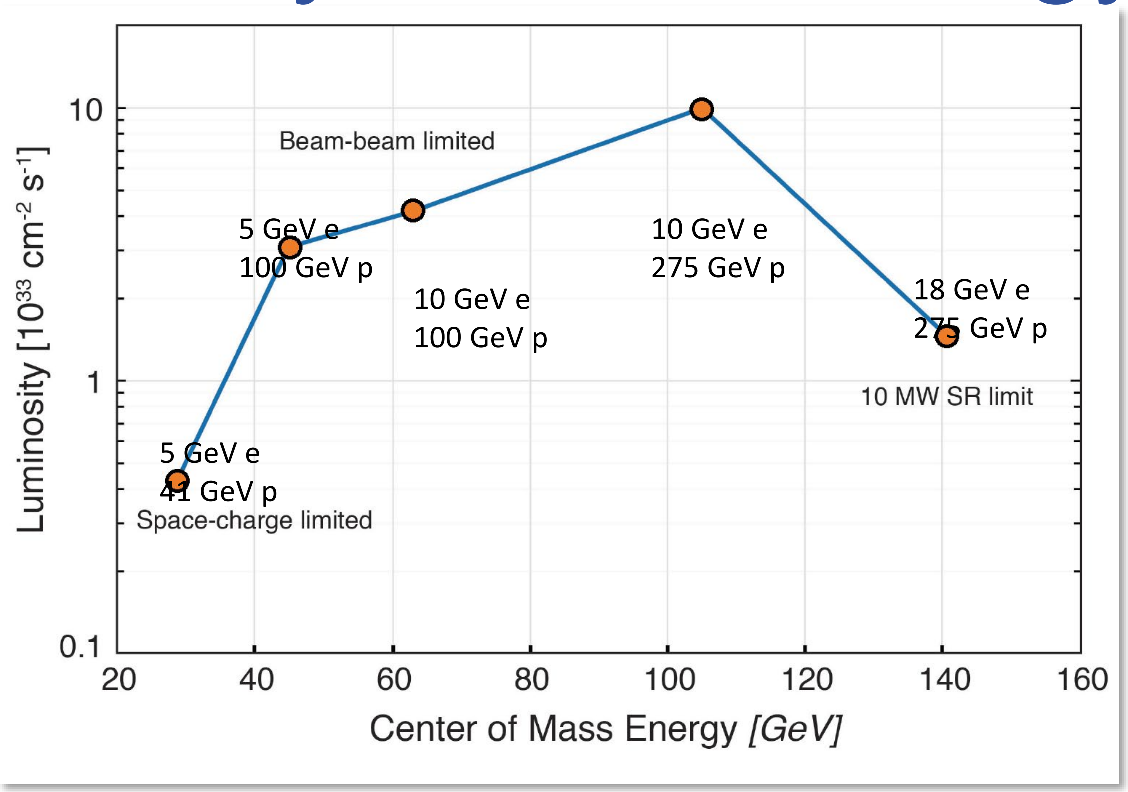
	proton	electron
no. of bunches	1160	
energy [GeV]	275	10
bunch intensity [10^{10}]	6.9	17.2
beam current [A]	1.0	2.5
ϵ_{RMS} hor./vert. [nm]	9.6/1.5	20.0/1.2
$\beta^*_{x,y}$ [cm]	90/4	43/5
b.-b. param. hor./vert.	0.014/0.007	0.073/0.100
σ_s [cm]	6	2
$\sigma_{\mathrm{d}p/p}$ [10^{-4}]	6.8	5.8
τ_{IBS} long./transv. [h]	3.4/2.0	N/A
L [$10^{33}\,\mathrm{cm}^{-2}\mathrm{sec}^{-1}$]	10.05	

- Hadron beam parameters similar to present RHIC, but smaller vertical emittance and many more bunches
- 2 hour IBS growth time requires countermeasures
- Electron beam parameters resemble a B-Factory, but with a large energy range and polarization

Parameters optimized for high luminosity at high energy

Alternative optimizations are possible, for example for high luminosity at low energy

Luminosity vs. CM Energy



- Parameter and IR optimization at 105 GeV center-of-mass energy
- Optimization yields $10^{34} cm^{-2} sec^{-1}$ luminosity at 105 GeV
- Alternative optimizations are possible, for example with an emphasis on luminosity at lower energies

Electron Storage Ring

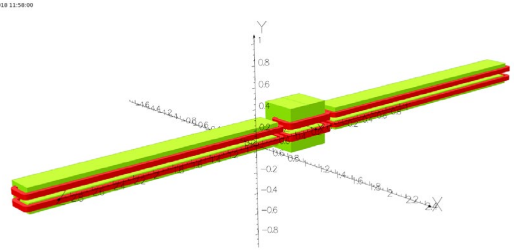
Composed of six FODO arcs with 60º /cell for 5 to 10 GeV
90º /cell for 18 GeV

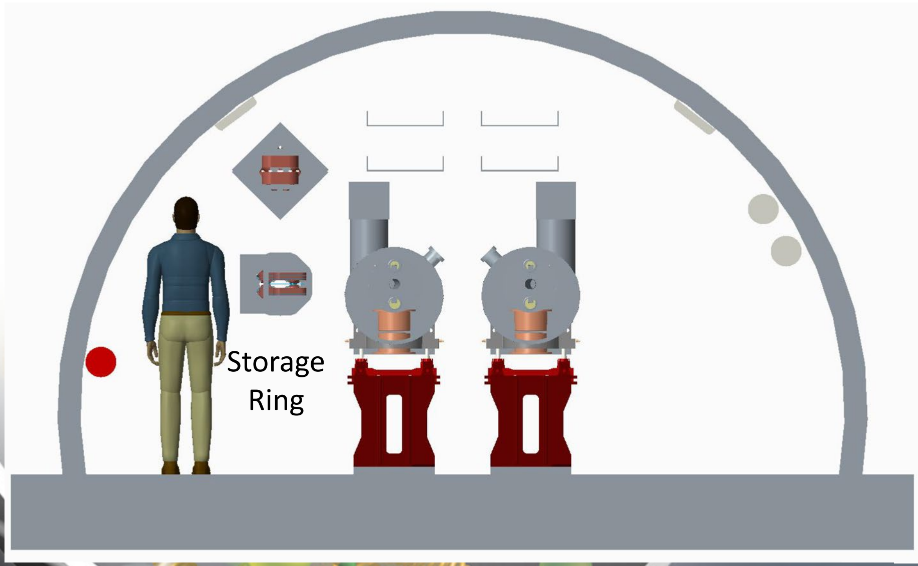
Super-bends for 5 to 10 GeV for emittance control

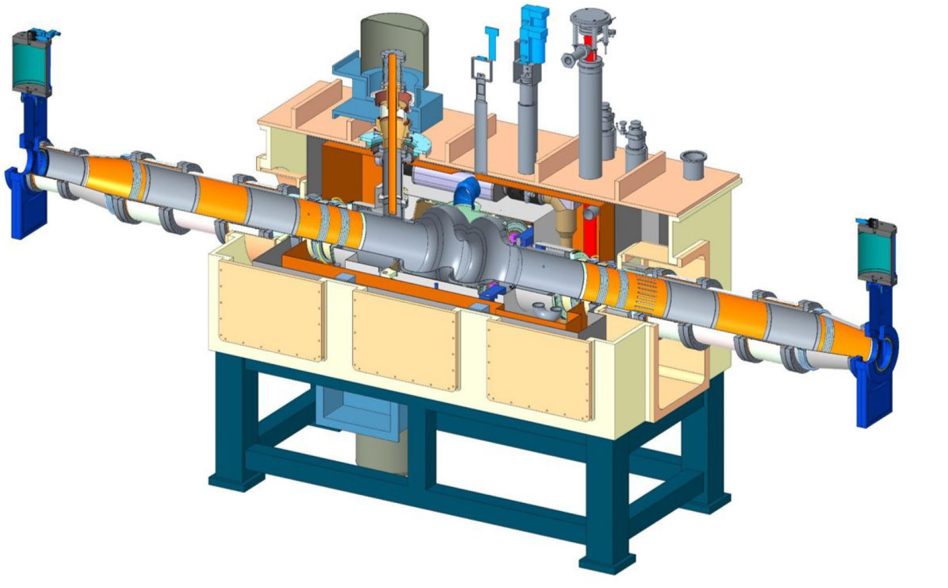
Straight sections with simple layout

Radiate approx. 10 MW for maximum luminosity parameters at 10GeV

591 MHz SRF





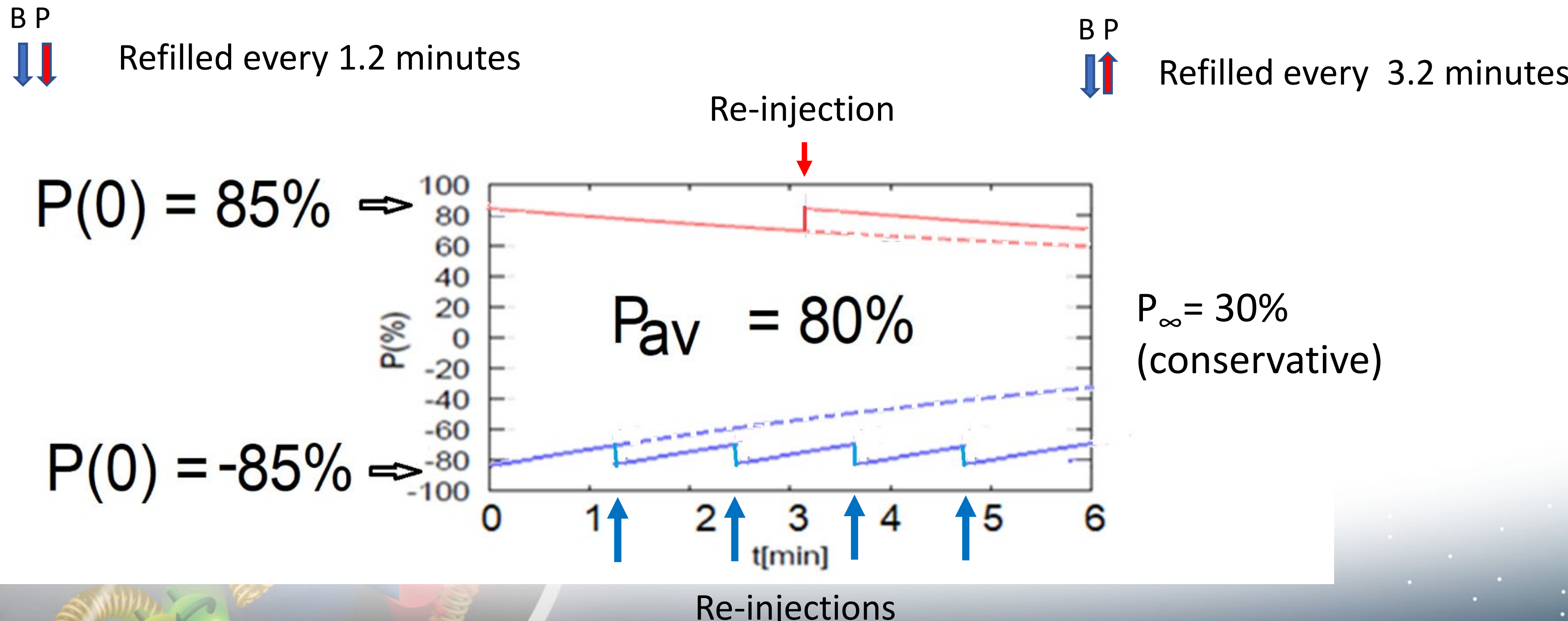


EIC Electron Polarization

- Physics program requires bunches with spin “up” and spin “down” (in the arcs) to be stored simultaneously
- Sokolov-Ternov self-polarization would produce only polarization anti-parallel to the main dipole field
- Only way to achieve required spin patterns is by injecting bunches with desired spin orientation at full collision energy
- Sokolov-Ternov will over time re-orient all spins to be anti-parallel to main dipole field
- Spin diffusion reduces equilibrium polarization
- Need frequent bunch replacement to overcome Sokolov-Ternov and spin diffusion

High Average Electron Polarization

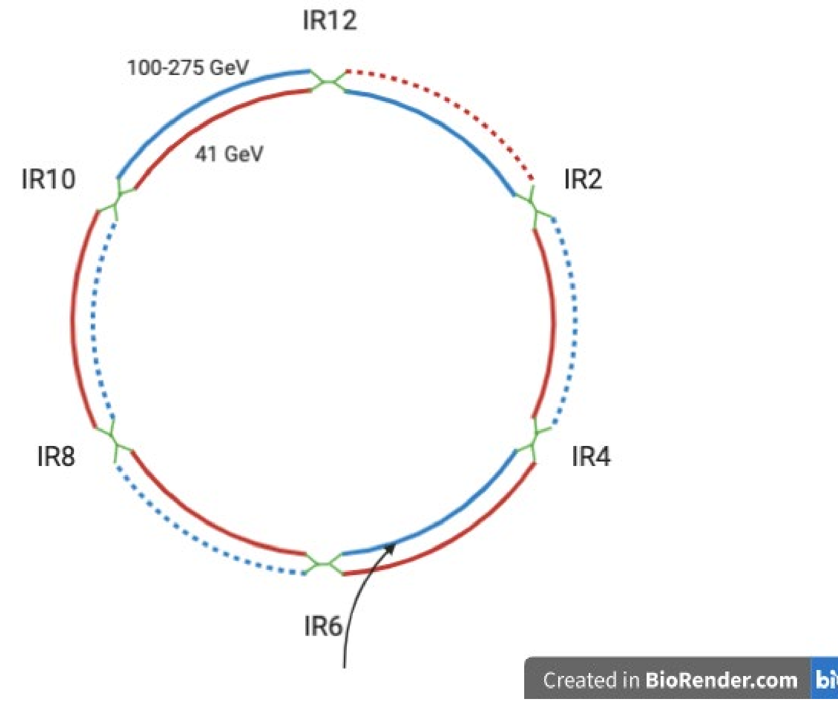
- Frequent injection of bunches with high initial polarization of 85%
- Initial polarization decays towards P_∞ < ~50%
- At 18 GeV, every bunch is replaced (on average) after 2.2 min with RCS cycling rate of 2Hz



Rapid Cycling Synchrotron as Full Energy Polarized Injector

- Both the strong intrinsic and imperfection resonances occur at spin tunes:
  - **Gϒ** = nP +/- Qy
  - **Gϒ** = nP +/- [Qy] (integer part of tune)
- To accelerate from 400 MeV to 18 GeV requires the spin tune ramping from
  - **0.907 < Gϒ < 41.**
- If we use a periodicity of P=96 and a tune Qy with an integer value of 50 then our first two intrinsic resonances will occur outside of the RCS energy range:
  - **Gϒ**1 = 50+ν_y (ν_y is the fractional part of the tune)
  - **Gϒ**2 = 96 – (50+ν_y) =46-ν_y
  - Imperfection resonances will follow suit with the first major one occurring at **Gϒ**2 = 96 – 50 = 46

Hadron Ring



- Existing RHIC facility will be re-purposed as EIC hadron storage ring
- Beam parameters are similar to RHIC, except number of bunches and vertical emittance
- Need to counteract intra-beam scattering

Counteracting Intra-beam Scattering

- Performed Analysis of Alternatives (DOE req.) in summer 2020:
  1. No cooling (or other countermeasure): $4{*}10^{33} cm^{-2} sec^{-1}$ peak luminosity
  2. Strong hadron cooling, using novel concept (CeC): $10{*}10^{33} cm^{-2} sec^{-1}$ peak luminosity
  3. Frequent on-energy hadron injection every 1-2 hours (requires significant work on layout of both RHIC hadron rings): $10{*}10^{33} cm^{-2} sec^{-1}$ peak luminosity
  4. Modify hadron ring layout, but pursue cooling at the same time and decide later: $10{*}10^{33} cm^{-2} sec^{-1}$ peak luminosity
- Chosen alternative: Strong hadron cooling

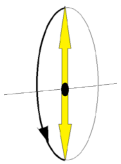
Hadron Storage Ring Modifications

- Insertion of pre-coated sleeves improve conductivity and reduce SEY
- Rebuild injection area with faster kickers to accommodate shorter bunch spacing
- Remove energy-limiting DX separator dipoles
- Inner arc between IRs 10 and 12 for circumference matching during 41 GeV low-energy operation
- (Energy range from 100 to 275 GeV can be covered by radial shift)

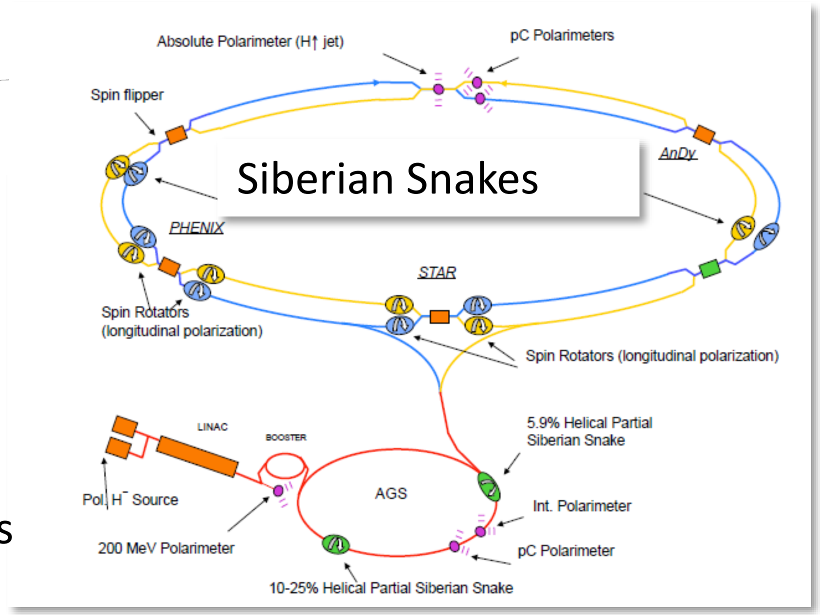
EIC Hadron Polarization

EIC will fully benefit from present RHIC polarization and near future upgrades

Measured RHIC Results with Siberian Snakes:



- Proton Source Polarization 83 %
- Polarization at extraction from AGS 70%
- Polarization at RHIC collision energy 60%



Planned near term improvements:

AGS: Stronger snake, skew quadrupoles, increased injection energy

➔expect 80% at extraction of AGS

RHIC: Add 4 snakes to 2 existing, no polarization loss

➔ expect 80% polarization in RHIC and eRHIC

Expected results obtained from simulations which are benchmarked by RHIC operations

Polarized ^{3}He in EIC with six snakes

Achieved ~85% polarization in 3He ion source

Benchmarked simulations:

Polarization preserved with 6 snakes, at twice the design emittance

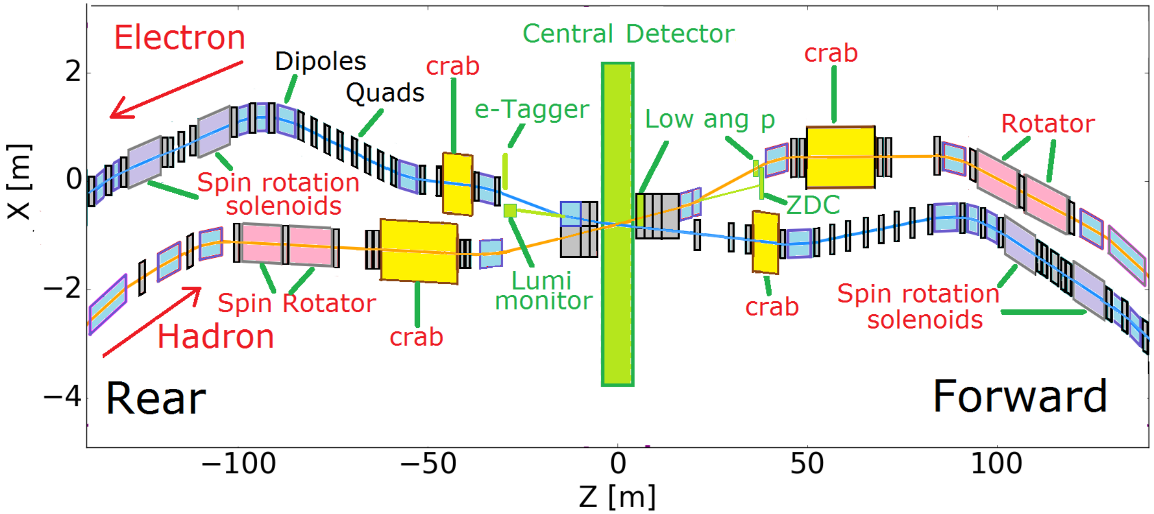
Polarized Deuterons in EIC:

Requires tune jumps in RHIC to overcome few intrinsic resonances

Benchmarked simulation shows 100% spin transparency

No polarization **loss** expected in the EIC hadron ring

Interaction Region



- +/- 4.5 m machine-element free space for central detector
- 25 mrad total crossing angle
- Transverse momentum acceptance down to 200 MeV/c
- Peak magnetic fields below 6T (NbTi sufficient)
- Most magnets direct-wind; few collared magnets
- A second IR is desirable, but not in scope. Overall machine design has to take second IR into account (beam dynamics, pathlength, etc.)

CD-1 Status

- Performed a series of reviews November to January towards CD-1
- All reviews were very positive, and recommended to be granted CD-1 by DOE
- Currently awaiting finalization of required paperwork
- CD-1 Approval Target Date: June 28, 2021

Topical Reviews

- EIC design has matured, and CD-2 is expected in about two years
- Now is the last chance to make major design changes
- Started series of topical reviews to make sure we are on the right track (Reviews on Beam-beam, Dynamic Aperture, Polarization, Collective Effects already done. More to come over next six months or so)

Summary

- The EIC is designed to collide highly polarized electron and light ion (p, d, h) beams, as well as unpolarized heavy ions
- Arbitrary spin patterns ("up" and "down") in both beams are provided by injectors
- Dedicated design of the rapid cycling electron synchrotron (RCS) allows polarization preservation all the way up to 18 GeV
- Additional Siberian snakes in the hadron ring will provide 100 percent polarization preservation during the ramp
- EIC reaches a peak electron-proton luminosity of

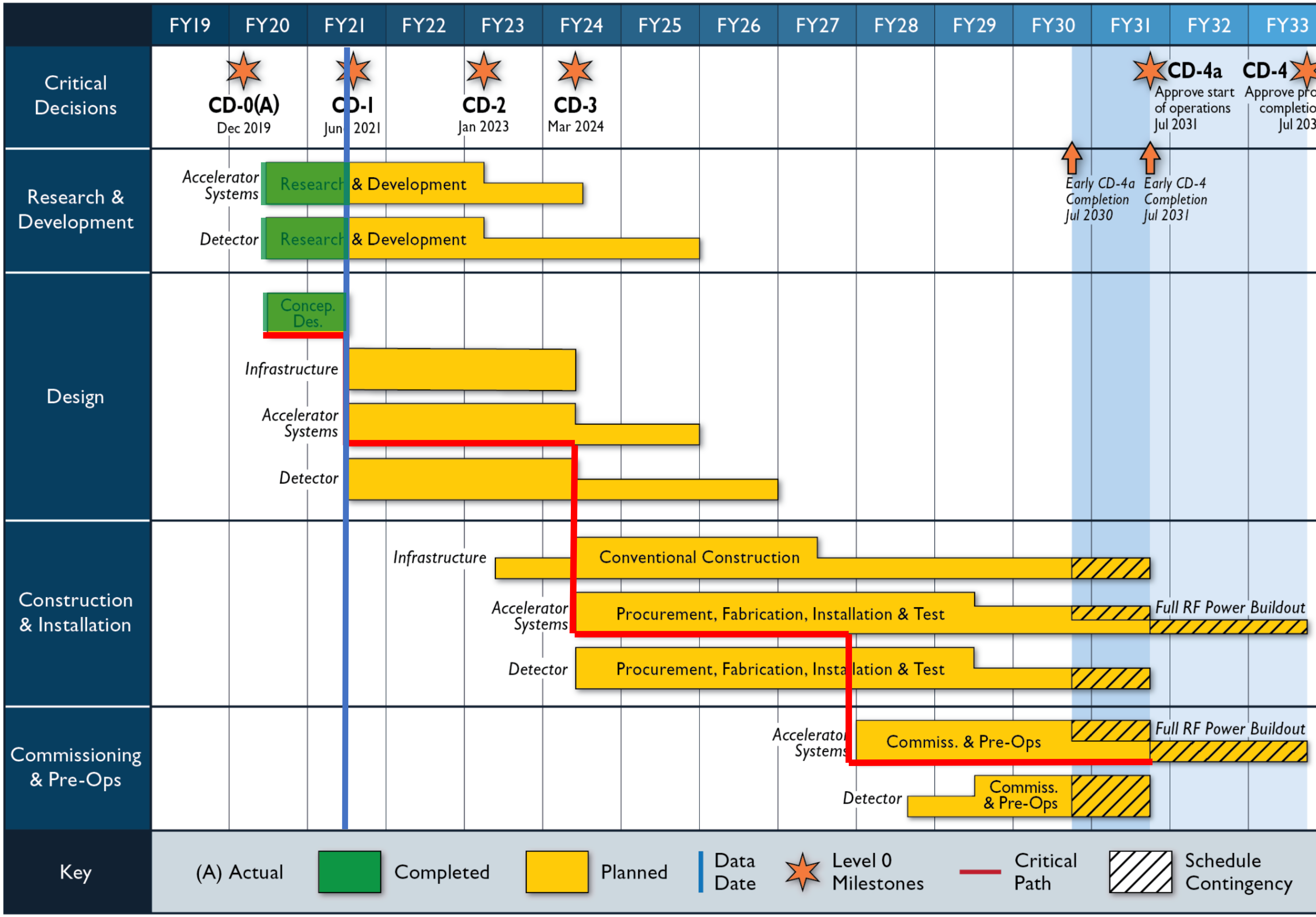
$$\mathbf{L = 10^{34} cm^{-2} s^{-1}}$$

at 105 GeV center-of-mass energy

- Alternative parameter schemes are possible, for example for optimization at lower center-of-mass energy
- CD-1 is imminent; gearing up for path to CD-2

Backup Slides

Schedule



FY19 FY20 FY21 FY22 FY23 FY24 FY25 FY26 FY27 FY28 FY29 FY30 FY31 FY32 FY33
Critical Decisions
CD-0(A) Dec 2019
CD-1 Jun 2021
CD-2 Jan 2023
CD-3 Mar 2024
CD-4a Approve start of operations Jul 2031
CD-4 Approve proj. completion Jul 2033
Early CD-4a Completion Jul 2030
Early CD-4 Completion Jul 2031
Research & Development
Accelerator Systems
Research & Development
Detector
Research & Development
Design
Concep. Des.
Infrastructure
Accelerator Systems
Detector
Construction & Installation
Infrastructure
Conventional Construction
Accelerator Systems
Procurement, Fabrication, Installation & Test
Full RF Power Buildout
Detector
Procurement, Fabrication, Installation & Test
Commissioning & Pre-Ops
Accelerator Systems
Commiss. & Pre-Ops
Full RF Power Buildout
Detector
Commiss. & Pre-Ops
Key
(A) Actual
Completed
Planned
Data Date
Level 0 Milestones
Critical Path
Schedule Contingency

Path To CD-2 – Near Term

Date	Description
Starting March 2021	Define TJ/BNL Scope
April 12, 2021	EIC Council Meeting
April 21-22, 2021	EIC Retreat with Level 2 WBS Managers/Deputies
Starting May 2021	Update Cost and Schedule to start preparing for setting the baseline
April 29-30, 2021	EIC Project Advisory Committee Meeting [Agenda-TJ Scope, Relationship with C-AD, Detector Path Forward)
Starting May 2021	Technical Reviews (see next slide for details)
May 19, 2021	**Office of Nuclear Physics/Office of Project Assessment Status Mtg**
June 28, 2021	**CD-1 ESAAB**
September 22, 2021	Machine Advisory Committee Meeting
September 30, 2021	WBS Level 2 Requirements Documents Complete
September 30, 2021	Global Requirements Document Complete
September 2021	Project Advisory Committee Meeting
September 2021	International Accelerator Workshop

Path To CD-2 – Technical Reviews

Date	Description
May 10, 2021	Beam-Beam Effect Technical Review
May 11, 2021	Dynamic Aperture Technical Review
May 21, 2021	Beam Polarization Technical Review
June 4, 2021	Collective Effects Technical Review
June 17, 2021	Superconducting RF Design Technical Review
June 2021	Superconducting IR Magnets Technical Review
July 2021	Interaction Region Design and Detector Machine Interface Technical Review
October 2021	ESR/HSR Vacuum Systems and Impedance Technical Review
November 2021	Pulsed Devices Technical Review
December 2021	Strong Hadron Cooling Technical Review
January 2022	Controls Systems Technical Review
February 2022	Installation Workshop
March 2022	Radiation Shielding Review

Path To CD-2

Date	Description
Oct 5, 2021	Post Documentation for OPA Status Review
Oct 12, 2021	Post Presentations for OPA Status Review
Week of Oct 18, 2021	**OPA Status Review**
Dec 1, 2021	Detector Proposals Submitted
March 2022	Decision on Project Detector
March 2022	Start EVMS
~April 2022	**OPA Status Review – Confirm schedule for CD-2 Reviews**
April – June 2022	Preliminary Design Reviews
~July 2022	CD-2 Director's Review
~September 2022	**CD-2 OPA/ICR Reviews**
January 2023	**CD-2 Approval**